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DETERMINATION OF THE SOLAR ENERGY MICROCLIMATE OF THE UNITED STATES USING SATELLITE DATA

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DETERMINATION OF THE SOLAR ENERGY MICROCLIMATE OF THE UNITED STATES USING SATELLITE DATA

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FINAL REPORT

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ABSTRACT

The report presents successful results of determining total solar energy reaching the ground over the United States using measurements from meteorological satellites as the basic data set. The methods of satellite data processing are described. They are based on many years of prior experience, as well as hardware and computer programs, related to quantitative analysis of meteorological satellite data. Uncertainty analysis and comparison of results with well-calibrated surface pyranometers are used to estimate the probable error in the satellite-based determination of ground insolation. It is 10-15% for daily information, and about 5% for monthly values. However, the natural space and time variability of insolation is much greater than the uncertainty in the method. The most important aspect of the satellite-based technique is the ability to determine the solar energy reaching the ground over small areas where no other measurements are available. Thus, it complements the widely-spaced solar radiation measurement network of ground stations.

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1.0 Introduction

This Final Report under Grant NAS5-22372 presents results of research during the sixteen-month duration of the grant: June, 1976 - October, 1977. Several earlier reports were submitted as required. Support for the research was suddenly terminated when NASA's Office of Energy Programs was excised from the fiscal year 1977 budget. Despite this fact, the tedious development of the satellite data processing methods and computational algorithms have demonstrated feasibility of the satellite-based method. Interest by both scientists and solar energy applications specialists has been extraordinarily high as measured by requests for the preliminary results of the study and by letters and calls inquiring about the method. In our opinion the positive results presented in this report indicate the advisability of continued research and demonstration of methods for determining the solar energy reaching the ground using satellite data.

Atmospheric scientists have studied solar energy for many years because of its interaction with clouds and gases in the atmosphere, and because of the surface heating due, in part, to solar energy reaching the ground. Both effects influence the thermal and dynamic state of the atmosphere and are important for weather forecasting. Indeed, the U.S. network of solar energy measurements was started and is maintained by the National Weather Service at their stations.

With the advent of meteorological satellites in the 1960's, and the establishment of NOAA's operational satellite program shortly thereafter, atmospheric scientists used these new platforms to obtain measurements of solar energy reflected from the earth and atmosphere. The initial interest focused on the atmospheric problems noted above

(Hanson, et al., 1967; Vonder Haar and Hanson, 1969). Throughout the course of this work the radiation specialists working on solar energy applications and on atmospheric problems kept in close contact through such groups as the Committee on Radiation Energy of the American Meteorological Society. The first author is a former chairman of this committee. At a special meeting to foster such coordination, sponsored by NSF (RANN) and organized by NOAA - the Solar Energy Data Workshop, November, 1973 - we proposed the method to determine the solar energy reaching the ground using measurements from meteorological satellites (Vonder Haar, 1974). During the following year, the research method was discussed and refined by the authors and their colleagues at the Department of Atmospheric Science, Colorado State University. At CSU, in the same College of Engineering, a larger, parallel effort by engineers including George Löf and Susumu Karaki developed a nationally recognized program of solar energy applications research. We continue to benefit from discussions with these engineers and scientists. Initially, the research leading to our larger effort with NASA was supported by a small grant from the State of Colorado, through its Colorado Energy Research Institute.

During the 1974-75 period the solar energy data needs of users were specified in increasing detail. Many groups participated and the Report and Recommendations of the above mentioned Solar Energy Workshop (Turner, ed., 1974) contains typical results. In general, information is required about the (X,Y,T) variation of both direct solar radiation and total (direct + diffuse) radiation. The concentrators require input about the direct, while collectors (e.g. used for heating and cooling systems) need total solar information. Certain spectral regions are of special interest for photovoltaics, yet most information demanded by users can be supplied

by total spectral measurements for close approximation. The statistics of the energy reaching the ground are often as important to users as the mean value data. Variability of solar energy over the U.S. has been studied using the past records collected at the few weather stations having good continuous measurements from either pyranometers (radiometers) or sunshine recorders (see for example Pack and Korshover, 1974; Angell and Korshover, 1975). The solar energy supply is characterized by both high spatial and temporal variability. Time scales from hours to years show variability.

It is precisely because of this high variability that satellites are important measurement platforms for assessing our solar energy resource. Some important considerations are:

1) Clouds are the principal modulators of the solar energy reaching the ground; meteorological satellites are designed to measure clouds. (See Figure 1.1 for a typical satellite photograph over the U.S.)

2) The satellite radiometers have high ground resolution, from 1 to 6 km, and are thus capable of resolving small regions of special interest (see Figure 2 in Appendix E for a high resolution view of the Lake Superior/Duluth area).

3) Output from the satellite radiometer is digital (quantitative), thus amenable for computer processing (see again Figure 2, Appendix E).

4) The satellite data are available from operational satellites, an integral part of NOAA's weather observation system, as frequently as every 10 to 30 minutes.

Figure 1.1 The photos can cover large regions showing clouds, snow and terrain features.

5) The entire U.S. is viewed with the <u>same</u> instrument reducing problems of intercalibration of many instruments (e.g. at ground stations) and thus facilitating the intercomparison of the insolation between different sites.

However, it is a major step between the availability of the satellite images and their potential yield of solar energy information. The data processing system and algorithms noted in the following sections and the appendices to this report were the results of a lengthly research effort. This <u>processing system</u> for determination of solar energy reaching the ground considers several special aspects of the satellite data. Calibration and location of satellite data were based on more than ten years experience in such research. The important variable of surface reflectance and attenuation of solar energy by dust and water vapor in the atmosphere had to be incorporated into the processing system. Here we've drawn upon experience in the use of the weather data and on special techniques and computer programs to account for radiative energy transfer through the atmosphere. Finally, the sheer volume of satellite data dictates that special hardware methods for processing data be used. Most of these were also available from previous meteorological satellite research at Colorado State University, and were adapted for use in the solar research project.

Such a major undertaking was prefaced by both possibility-of-success and worth-of-success considerations. Our initial proposal to NASA, based upon work sponsored by the State of Colorado, included a complete uncertainty analysis of the proposed method. We estimated an uncertainty of less than 9-10% for the determination of the magnitude of solar energy reaching the ground. Of course, we could be sure that the spatial variation, or gradient information about insolation would be of very high

accuracy even if the absolute values were offset. (Results of our subsequent research, as described in the following sections, showed this to be a good estimate.) The Solar Energy Data Workshop Report contains a recommendation that solar radiation reaching the ground be determined with less than ± 5% systematic error. However, the discussion of this goal at the workshop was extensive and included the points that engineers are presently using data, where available, containing 10-15% systematic error. From the point of view of the satellite-method, our error estimates were not based on the use of corrections to the satellite-inferred values by a high quality set of measurements at the surface. This is certainly part of the proposed concept and thus we should do even better than the estimates would indicate. Namely, the satellite-determined output will ultimately be adjusted to the new high quality data presently available from NOAA's "baseline" stations at Mauna Loa, Samoa, and Barrow (Hanson, 1971) and to the new, upgraded network over the United States (Riches, et al., 1975). In summary, possibility-for-success of the proposed method is found to be high.

What about worth-of-success? At present and in the foreseeable future we have only about 35 to 40 high-quality solar energy measurement sites over the United States. When all lower accuracy radiometers and sunshine recording sites are included, we have at best 100 data points across the entire country. Many of these are so influenced by local conditions (e.g. urban effects) that they are unrepresentative of other locations only a few miles away. In addition, Pack and Korshover (1974) report that the spatial variation of monthly averaged sunshine between pairs of sites (e.g. Boston-Albany, Kansas City-St. Louis, Los Angeles-San Diego) can reach values of 20-30%. Of course, daily spatial variation

can be 300% because of weather conditions. Thus, how can the design engineer for a solar application project use such data from our surface network to consider a construction at a location without measurements? He interpolates only with great uncertainty or more prudently, designs an excessive margin into his solar energy system. Some studies have estimated the cost of such excessive margins. Houghton (1976) considered three sites and modeled the economic impact of uncertainty in insolation data. Using monthly average statistics from the past data set he determined that the sensitivity of annual fuel savings was about one dollar per year per percent difference in insolation multiplied by the homeowner's fuel cost per MBTU. Thus, better information, as from the satellite method, that reduces insolation uncertainty by 10% would save each homeowner approximately $55 per year for a fuel cost of $5.50 per MBTU. In a separate study the Solar Energy Data Workshop Report states that users estimated benefit-to-cost ratios of 700 to 800 per unit cost of new ground station radiometers. Better information about the average solar energy supply and more extensive data on variability are obviously of substantial worth.

Is the option of a tremendously increased ground-based network a real alternative? Instrument manufacturers have responded to the solar energy measurement need by discussing such proposals (Klein and Hickey, 1973; Katz, 1975) and manufacturing a variety of new solar energy radiometers. Some of these are of great importance to upgrading the few existing stations. However, the cheapest system which compares well with more expensive instruments (Silva Dias, et al, 1976) still entails about $500 per site for instrument plus digital recorder. Site acquisition, maintenance and calibration costs, all labor intensive, are additional.

In our opinion, the optimum approach to obtain the necessary and valuable solar radiation microclimate over the United States, and to keep updating the data set, is to:

a) maintain a limited number of very high quality surface radiation measurement sites;

b) fill the spatial gaps between such stations with a determination of solar energy reaching the ground based on satellite measurements.

The following sections describe the satellite method, the data sets already available, and results that demonstrate feasibility of the method.

2.0 Method of Determining Solar Energy Reaching the Ground Using Satellite Data

After Vonder Haar (1974) outlined the proposed methods, we refined the techniques to determine both total and direct beam solar energy reaching the ground in a set of papers (Vonder Haar and Ellis, 1975, Ellis and Vonder Haar, 1976). These papers are reproduced in their entirety in Appendix A to this report. As noted in Section 1.0 the methods are the results of many years of research using satellite measurements and radiation calculations to solve atmospheric research problems. Their adaptation to the determination of solar energy reaching the ground was a major result of the research presented in this report.

3.0 The Satellite and Weather Data Used in the Research

A principal objective of this study was to demonstrate a capability for determining total solar flux (insolation) at the ground, using earth orbiting satellite measurements of upwelling solar radiation flux. Thus, emphasis is placed on applying satellite data to the problem rather than depending largely on a broad based ground measurement network.

Satellite data which qualified in various degrees of "goodness" for the study are shown in Table 3.1. Some data sets are archived strictly as photo images and others as digital radiance values. All satellites listed in the table were in sun synchronous orbits sampling at just one local daylight sun time each day with the exception of SMS 1 and 2. An SMS satellite has a geostationary orbit such that the satellite subpoint is nearly fixed at one latitude and longitude. Each area element is sampled approximately every 1/2 hour. Most of these data are in imagery format with only a few intermittent digital sets being archived.

Satellite data actually used in this study are as follows: approximately 120 days of ESSA-9 imagery concurrently with Nimbus 3 digital radiance data for May 1969 through January 1970; daily digital data for the month of June 1975 from NOAA-4. (Some digital and imagery data from SMS 1 and 2 were acquired but were not processed because of a premature discontinuance of grant funding.)

To establish an empirical function for atmospheric absorption in cloudy atmospheres we required daily U.S. rawinsonde network observations and a reliable ground network of daily pyranometer measurements. For the June 1975 period there were just 9 sites in the National Weather Service ground network which recorded total daily insolation with well maintained Eppley Model II pyranometers. Absolute accuracy of this pyranometer is $\pm$ 5%. The 9 stations are shown in Table 3.2.

Daily ROAB's are also required so that computation of daily precipitable water (W) can be made. The W values are computed at each RAOB site and then objectively analyzed at 1000, 850 and 700 mb levels to fit the NWS

TABLE 3.1

SATELLITE DATA

SATELLITE	GRIDDED TIME	GRIDDED SPACE	IMAGERY[1]	DIGITAL[1]
ESSA 9	1430	6 NM	*	
NIMBUS 3	1130	200 KM		*
ITOS 1	1430	6 NM	*	
NOAA 2	0900	6 NM	*	*
NOAA 3	0900	6 NM	*	*
NOAA 4	0900	6 NM	*	*
SMS 1	1/2 HR	1/2-2 NM	*	
SMS 2	1/2 HR	1/2-2 NM	*	

[1]The * symbol indicates the format of the archival (Circa, 1976).

TABLE 3.2

STATIONS WITH EPPLY MODEL II PYRANOMETER DATA FOR JUNE 1975

	Daily	Hourly
Albuquerque, NM	*	*
Bismarck, ND	*	*
Caribou, ME	*	*
Ely, NY	*	
Las Vegas, NV	*	
Miami, FL	*	*
Oak Ridge, TN	*	
Phoenix, AZ	*	
Seattle-Tacoma, WA	*	

forecast grid spacing which is every 32nd fine mesh point (approximately 10 km on a side) of the satellite data grid. The generated W fields are, at a later step in the final insolation computation, interpolated in three dimensions to the fine mesh satellite data grid. A complete description of the various operations performed on each data set and how the data sets come together for a surface insolation computation appear in Appendix B.

4.0 Results of the Study

In this section the atmospheric absorption parameterization is discussed along with derived values of surface insolation from the satellite measurements. Following that, we present a comparison of satellite results with insolation climatologies from a ground network of measurements for a test of the satellite method.

4.1 Absorption Parameterization

As discussed in Ellis and Vonder Haar (1976) (in Appendix A-2) the fractional atmospheric absorption of solar energy (q_a) in a cloudy atmosphere[1] was found by Hanson (1971) to have an empirical relationship to optical pathlength (τ) in the form

$$q_a = C_1 + C_2\,\tau^{1/2}\ln\tau \qquad (4.1)$$

Hanson (1971) derived coefficients $C_1 = 0.117$ and $C_2 = 0.31$ by applying a least squares fit to q_a and τ, both of which were determined at a ground pyranometer site. Satellite data used in his study consisted of monthly mean values of medium resolution (50 km at satellite subpoint) Nimbus 2 scanning radiometer measurements. The value τ is a function of

[1] In this method the clouds scatter, but do not absorb the solar energy.

amount of cloud (measured from satellites) and water vapor optical depth (from RAOBS).

The daily q_a and τ values (determined from the method presented in Appendix B) for the nine ground based pyranometer locations for the month of June 1975 are plotted in Figure 4.1. The ground based set was limited in size to include only the well calibrated and maintained instruments within the NWS network of global insolation measuring stations. The curve in Fig. 4.1 is a least squares fit to Equation 4.1, the coefficients being C1 = 0.133 and C2 = 0.033.

There is a considerable amount of scatter of the points about the line of regression. The scatter of the values at each of the nine stations about the nine-station regression line was computed and is shown in Table 4.1. The scatter of daily values is on the order of 10 percent of the insolation received at the top of the atmosphere. The nine-station parameterization of q_a is within two percent at six of the stations and within six percent at the remaining three stations (average algebraic difference is defined as the q_a computed from Equation 4.1 minus the q_a computed at each station from Equation 1 in Appendix B averaged over the month).

The Miami and Seattle data sets were extracted from the nine station data set in order to assess the scatter of points observed in Fig. 4.1. These stations were selected as extreme cases of departure of q_a from the line of regression, i.e., the scatter at Miami is 13.6 percent and the average algebraic difference at Seattle is 6.0 percent. The plot of q_a versus τ for the two stations is shown in Fig. 4.2. A least squares line of regression of the form of Equation 4.1 was fitted to each data set in order to aid comparisons. The two curves are similar but differ

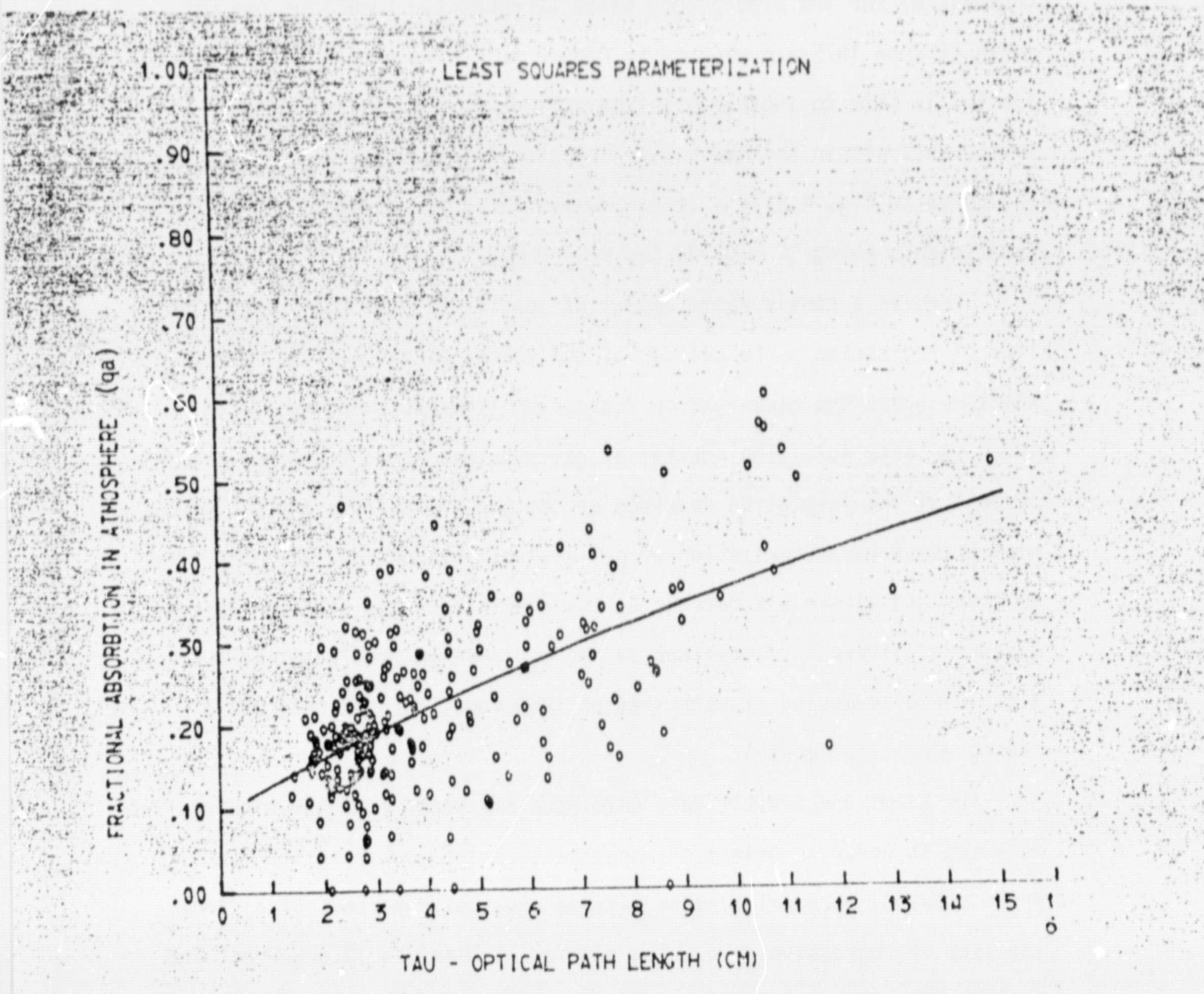

Figure 4.1 Least squares fit for daily values over 9 pyranometer sites.

TABLE 4.1

Differences between atmospheric absorption derived from a regression function and that derived as a residual of measurements.

Station	Avg. Algebraic Diff		Scatter	
	Percent	ly day^{-1}	Percent	ly day^{-1}
Albuquerque	-1.3	-13	6.4	63
Bismark	0.5	6	8.4	84
Caribou	0.4	4	8.1	81
Ely	-4.0	-40	9.6	96
Las Vegas	2.4	24	7.1	70
Miami	-1.5	-15	13.6	131
Oak Ridge	-1.9	-19	9.5	94
Pheonix	0.9	9	6.0	59
Seattle	6.0	59	9.7	96
Nine Stations	0	0	8.8	42

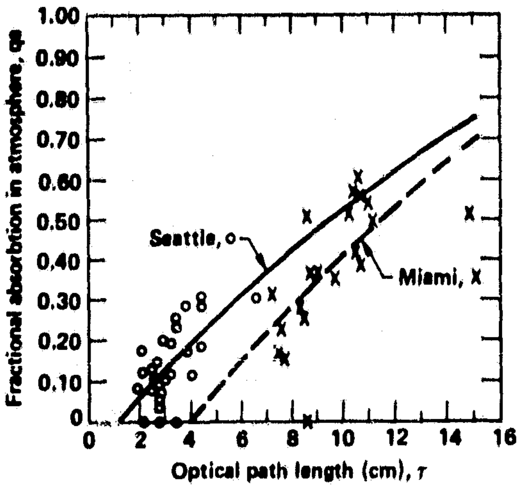

Figure 4.2 A daily plot of atmospheric absorption versus optical pathlength at two stations for the month of June 1975.

considerably from the nine-station curve of Fig. 4.1. The mean vertically integrated water vapor content of the atmosphere for June 1975 at Miami is 4.2 cm while at Seattle it is 1.6 cm. The larger precipitable water content at Miami accounts in general for the larger q_a at Miami but does not account for the large slope and the offset between the curves of Fig. 4.2. The offset may be caused by diurnal changes in cloud amount, and thus q_r, at Miami. The effect of a daytime average cloud cover (A_c) greater than that observed by the satellite during its overflight would be to reduce q_a by increasing q_r and to reduce τ (see Appendix B). Further assessment of the diurnal cloud change effect requires knowledge of $\frac{\partial q_r}{\partial A_c}$.

Appendix A2 shows that, q_s, the surface insolation away from the pyranometer location is determined from:

$$q_s = \frac{(1.0 - q_r - q_a)}{(1.0 - \rho_s)} \tag{4.2}$$

We obtain q_a, as discussed above, and q_r and ρ_s are measured from the satellite.

4.2 Satellite Derived Surface Insolation Maps

Prior to demonstrating a capability using the higher spatial resolution satellite data in June 1975 a study was done with medium resolution scanning data from the Nimbus 3 satellite (gridded at approximately 200 km on a side area) for the state of Colorado only. The original coefficients of Hanson (1971) were used in equation 4.1 to determine atmospheric absorption. Figure 4.3 shows these results for six grid areas covering Colorado. It is quite obvious that this large grid spacing is not ideal because of the large variety of climate classifications within each grid area, e.g. valley, mountain, plateau, desert, forest, and etc.

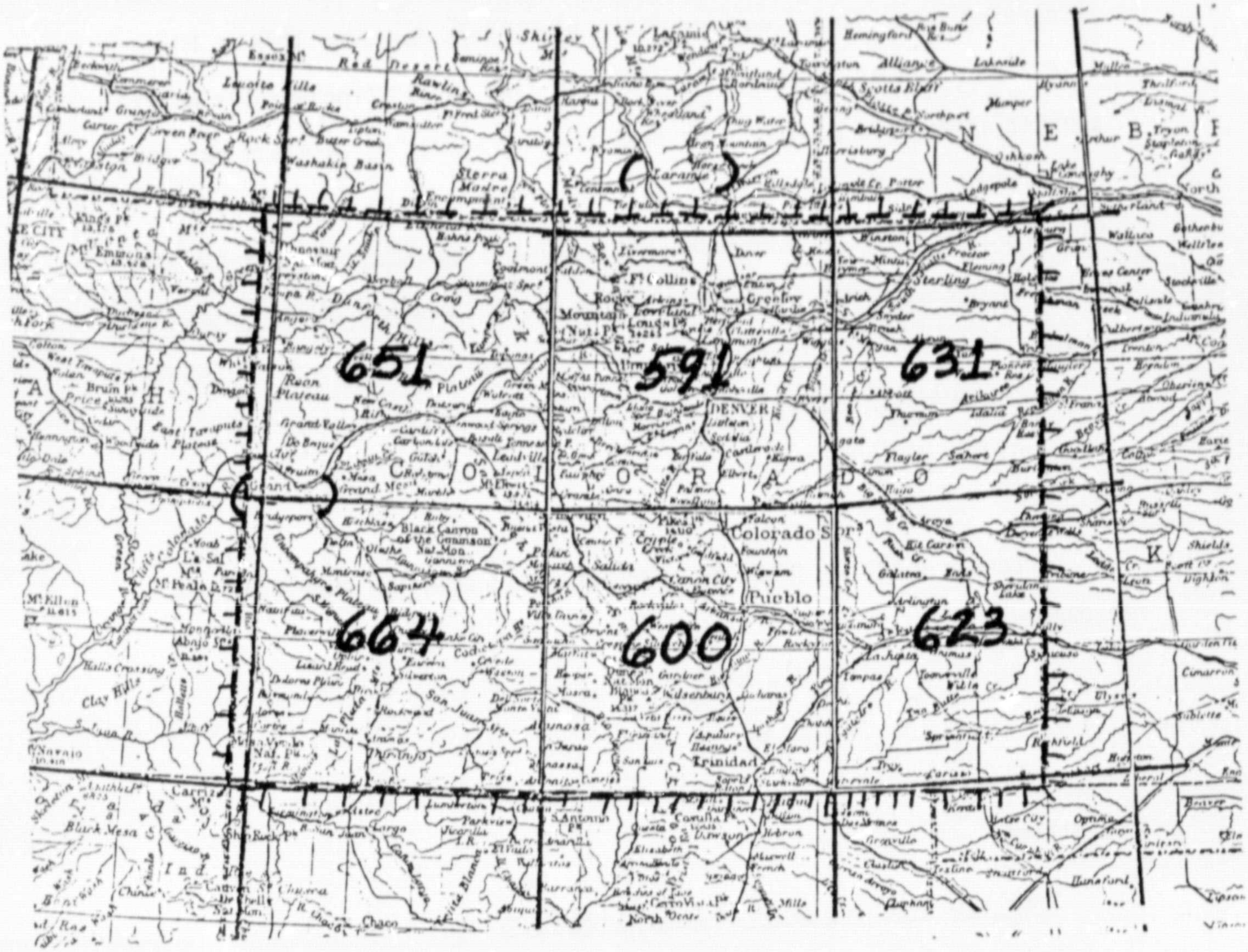

Figure 4.3 Satellite determined average daily surface solar insolation in Colorado for June 1969 (langleys/day).

Results from the higher resolution solution NOAA 4 scanning radiometer data are shown in Figure 4.4. The gridded results of our study are of such high spatial resolution that they would not give a good basis for comparison to other studies. Thus, every sixteenth grid point in each dimension was selected for the isoline analysis in Figure 4.4. The general features are in qualitative agreement with what one would expect because of cloudiness associated with various regions of the U.S. There are low values in the Pacific Northwest and New England States, and high values in Southwestern desert regions. (See Appendix E for further discussion.)

4.3 Comparison With Other Insolation Climatologies

The image in Figure 4.4 is compared with Figure 4.5, a mean June analysis derived from historical ground based measuremnnts (U.S. Climatic Atlas). Both figures are in langleys per day. Since the latter figure represents an average of many months of June measurements while the former is but for June 1975, only qualitative comparison will be made.

Agreement is seen in the two figures with low values in NW, NE and SE U.S. and with high values in West and Southwest U.S. A finger of low insolation extends northward into the Mississippi Valley which is restricted to the valley in the satellite results. Some disagreements are worth noting. A maximum appears in the satellite results over the Colorado Rocky Mountains which is undoubtedly a bias towards the morning hours at satellite observation time (9 a.m. local solar time) before midafternoon cloudiness begins -a frequent occurrence over the Rockies. The extension of the 600 ly/day contour in Figure 4.5 into NE Colorado was based on the Boulder, Colorado data - a station which is in the lee of the mountains and is subject to considerable mountain induced wave

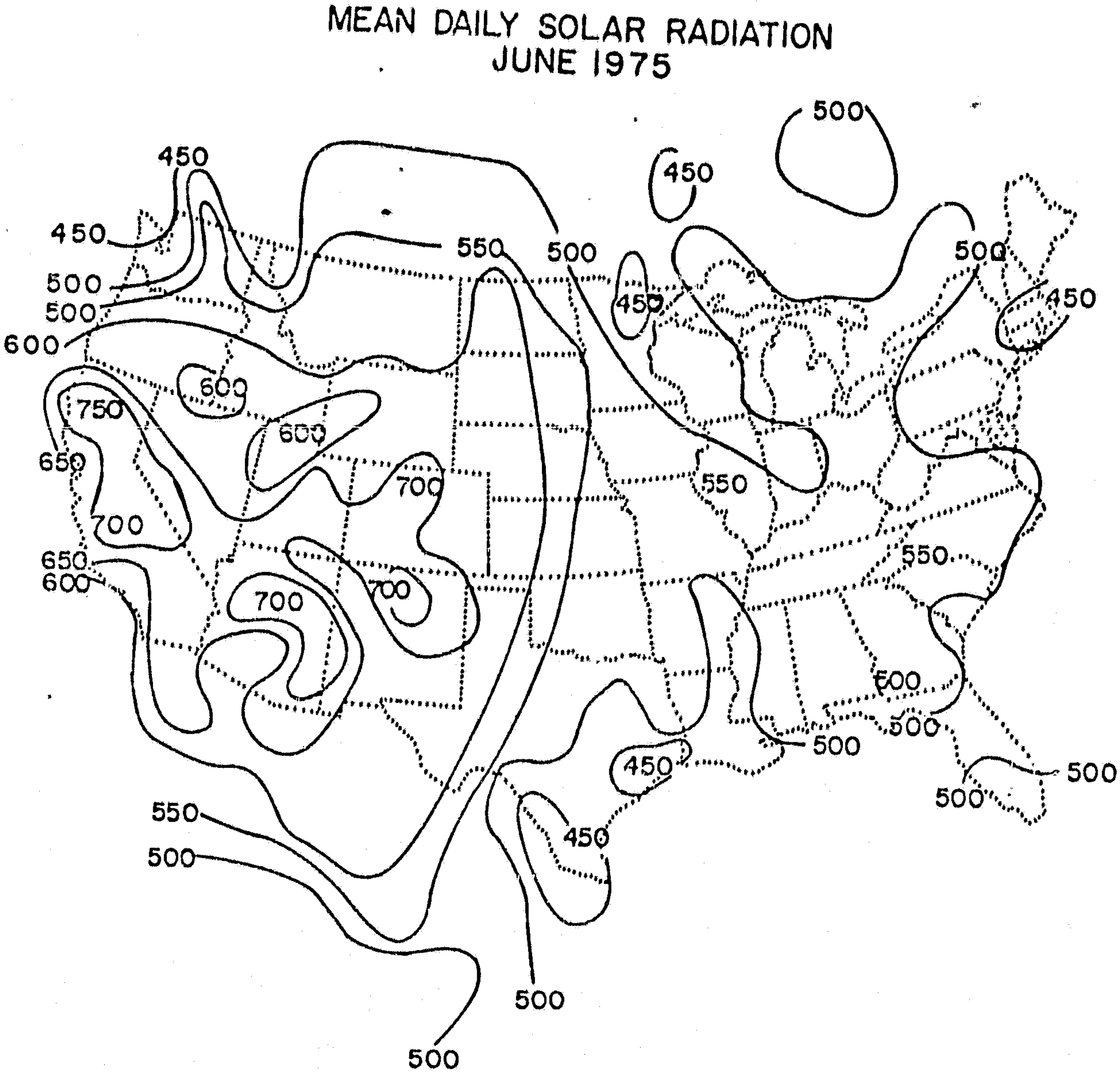

Figure 4.4 Mean daily solar radiation reaching the ground over the United States during June 1975 as determined from weather satellite observations. Values are in calories per square centimeter per day. (1 calorie/cm^2 day = 0.15 BTU per square foot per hour)

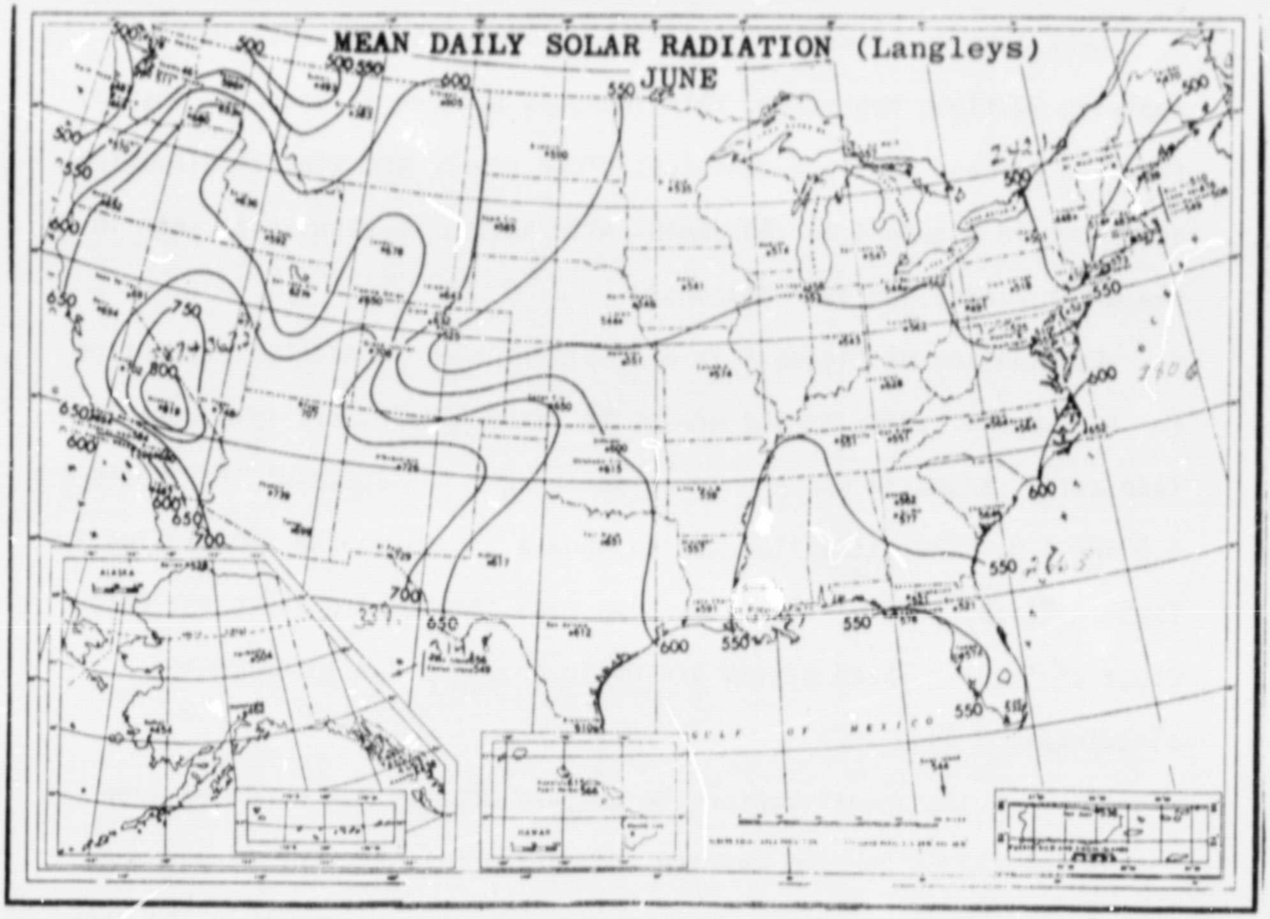

Figure 4.5 From the Climatic Atlas of the United States, U.S. Department of Commerce, Environmental Science Services Administration, Environmental Data Service, June, 1968.

and orographic cloudiness. The coarse grid satellite results indicate that the isolines to the east of Colorado are not to be extended westward into Colorado.

Mean June isolines of insolation, computed by Bennett (1965) applying multiple regression relationships between 12 years of insolation and percent possible sunshine, cloud cover, and station elevation, are shown in Figure 4.6. Agreement with satellite results is seen in the Great Plains and over Wisconsin.

Examination of Figure 4.7, a compilation of insolation statistics for a number of years at the ground by Texas A&M University, shows low insolation values in Eastern Texas which were not apparent in Figures 4.5 and 4.6. The satellite results show a trough in the 500 isoline in Eastern Texas. The satellite results also show minima along the Gulf Coast of Texas. These minima are quite possibly due to anamolous cloudiness in June 1975.

It is quite unsatisfactory to compare maps of one month of June statistics (1975) to time averages of many months of June in any more detail than was done above. However we were able to assemble the data on "percent of possible sunshine" as actually reported by the National Weather Service for June 1975 (Figure 4.8). Comparison of their map with the totally independent satellite results of Fig. 4.4 provides strong verification of the satellite method. Both the Minnesota and Gulf Coast minima detected by the satellite are shown in the surface sunshine data. Thus it does appear that except for regions which have a large daytime variability in cloud cover (Rocky Mountains, etc.), the sun synchronous, once-a-day satellite results are comparable to spatially smoothed results from point measurements of the ground-based pyranometers.

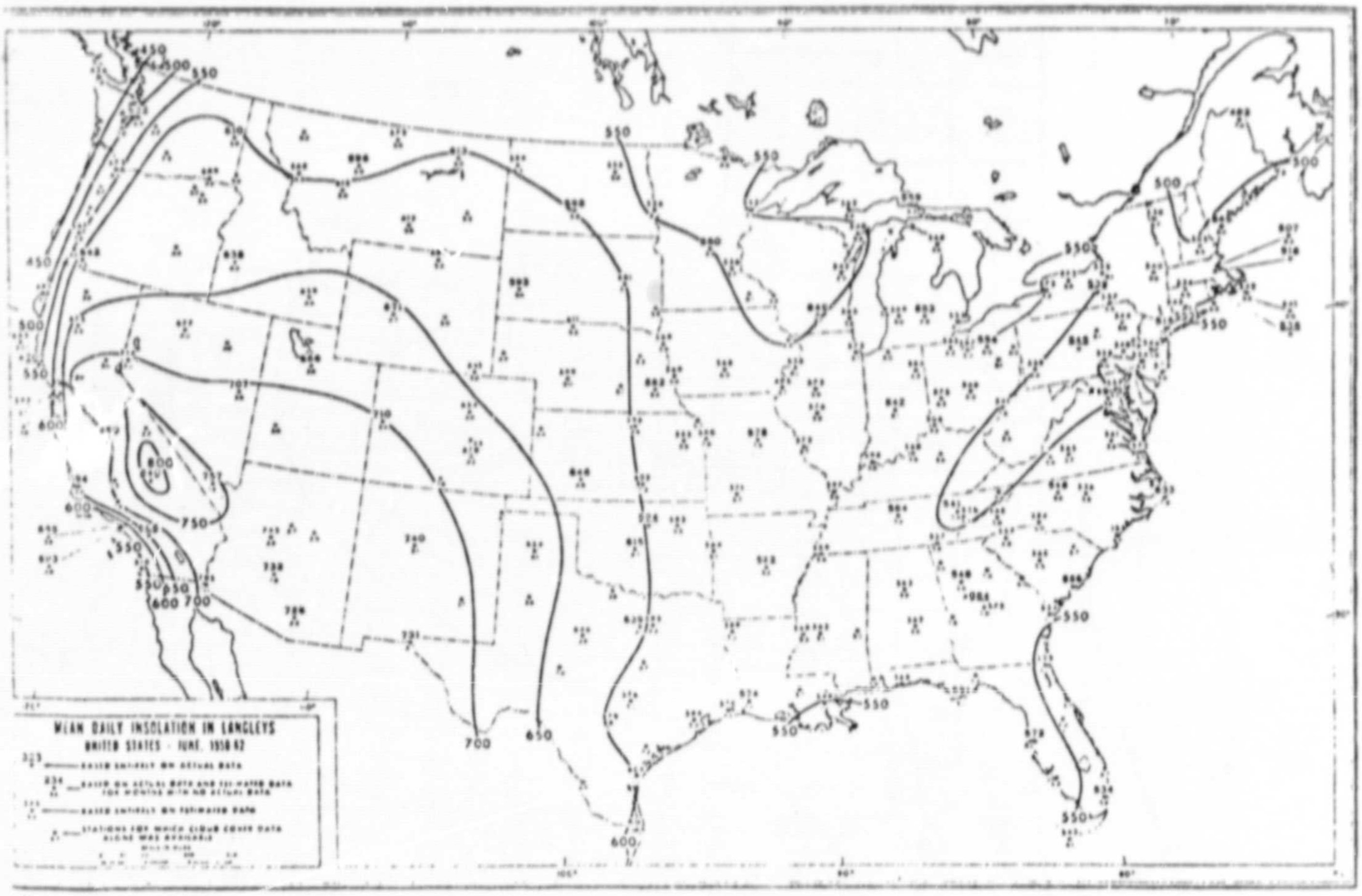

Figure 4.6 From "Monthly Maps of Mean Daily Insolation for the United States" by I. Bennett. Presented at the Twelveth Conference on Radar Meteorology, Norman, Oklahoma, October 17-20, 1966.

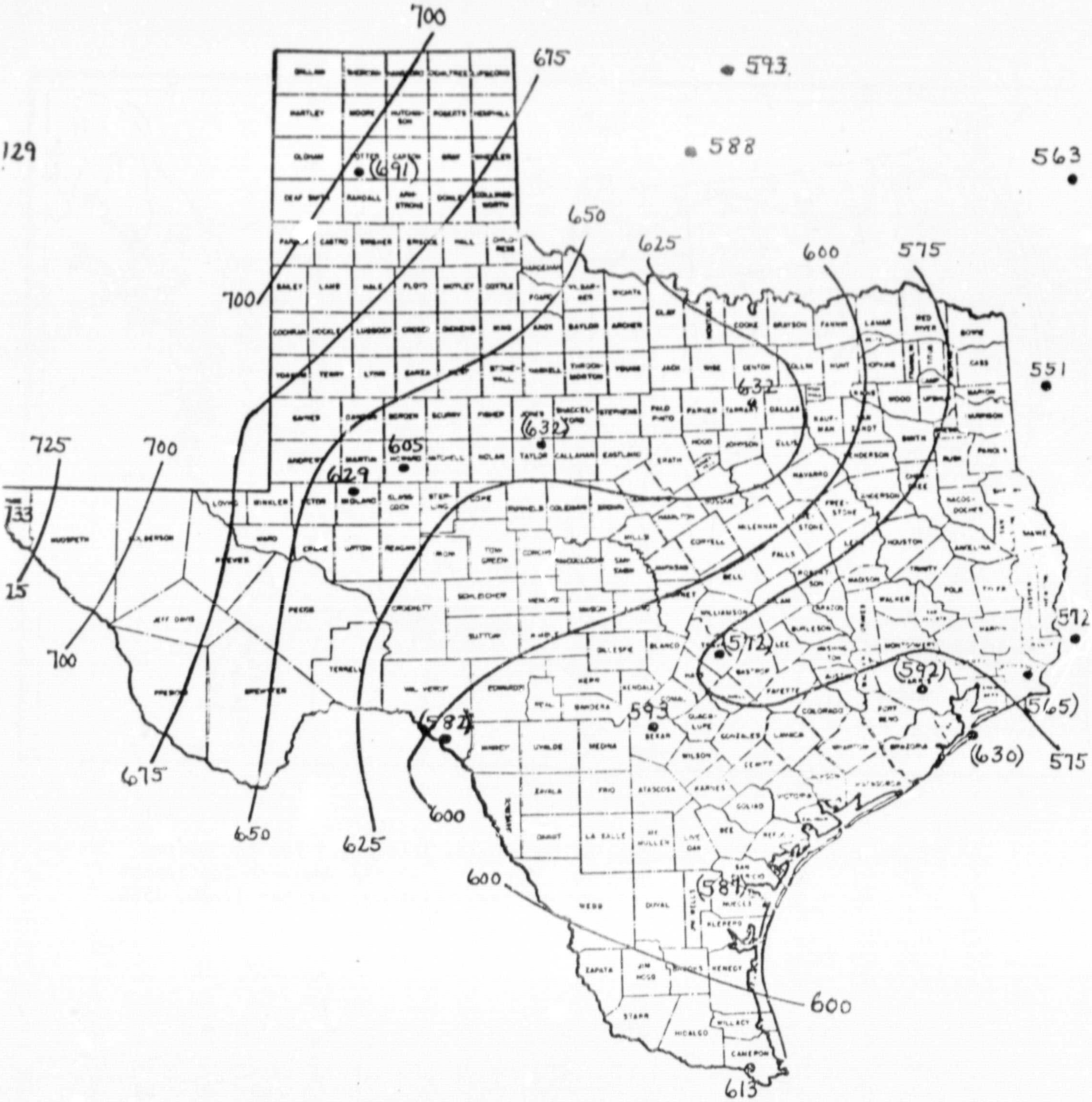

Figure 4.7 Mean solar radiation in langleys: June.

PERCENTAGE OF POSSIBLE SUNSHINE, JUNE 1975

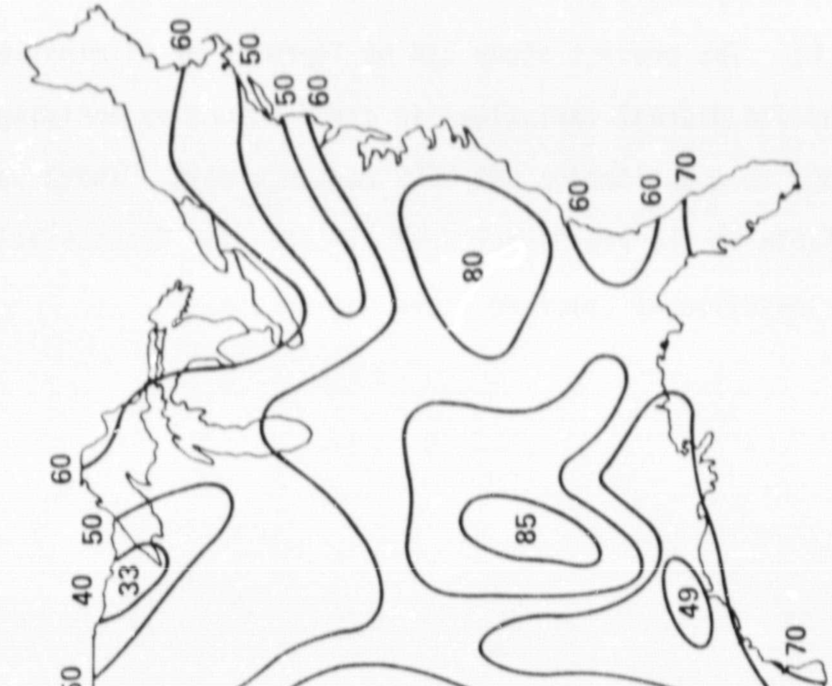

Figure 4.8

Zooming in to use the satellite results at full spatial resolutions will give insolation statistics which would otherwise be available only from a spatially dense ground network of measurements (see example in Appendix E). The present study can be improved by eliminating errors due to daytime diurnal variations in cloud amount by applying the same methodology to quantitative SMS/GOES radiance data. These data are now available at the new Direct Readout Satellite Groundstation (Fig. 4.9) recently installed at Colorado State University.

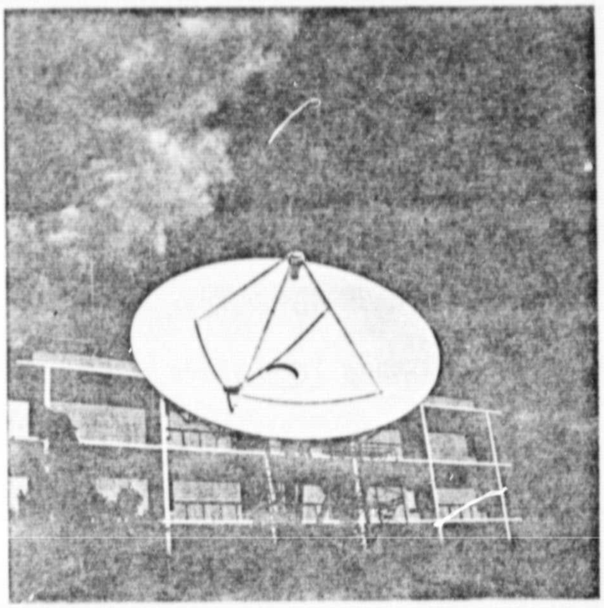

Figure 4.9 CSU Direct Readout Groundstation Antenna

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We thank our many colleagues at Colorado State University who aided our research. Dr. Lester Machta of NOAA stimulated our early interest in the problem. Mr. Michael Riches of NOAA provided access to the surface pyranometer data. Wayne Bowers of CSU did a fine programming job, considering the magnitude and wide variety of data sets and tapes used in the research. David Loranger of CSU determined the radiometric conversion coefficient for the visible channel data of the NOAA-4 scanning radiometer. Dr. Matthew Thaekakara of NASA was technical monitor, and Mr. John Anderson from NASA's Office of Energy Programs had the foresight to launch the satellite-based solar energy estimate program. The National Center for Atmospheric Research provided substantial computer time, essential to the results presented in the report.

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SOLAR ENERGY MICROCLIMATE AS DETERMINED FROM SATELLITE OBSERVATIONS

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Appendix A-1

ABSTRACT

A method is presented for determining solar insolation at the earth's surface using satellite broadband visible radiance and cloud imagery data, along with conventional "in situ" measurements. Conventional measurements are used to both tune satellite measurements and to develop empirical relationships between satellite observations and surface solar insolation. Cloudiness is the primary modulator of sunshine. The satellite measurements as applied in this method consider cloudiness both explicitly and implicitly in determining surface solar insolation at space scales smaller than the conventional pyranometer network.

INTRODUCTION

Solar energy received at the earth's surface is viable as an additional source of energy. There is now a need for more knowledge about its variability in space and time so the solar collector, concentrators, and storage devices may be designed for optimum performance.

Previously, surface measurements have been used to assemble regional to global spatial scale maps of monthly means of surface solar energy. These have been put together by various authors, some of which are: Fritz and McDonald (1949), Ashbel (1961), Löf, et al. (1966), and Bennett (1965). Cloudiness is the primary modulator of solar energy. Satellites can observe cloudiness over large areas with more spatial integrity than surface observations. Satellite measurements now available allow solar energy determination over a wide range of spatial scales much smaller than the conventional network permitted in the earlier works. Additionally, satellite measurements permit estimates to be made in areas where no conventional data are available.

Broadband shortwave radiances (0.3 to 3μm) measured by the satellite along with cloudiness derived from satellite imagery are used to compute surface solar energy. Conventional surface pyranometer measurements are used to "tune" the satellite measurements.

SOLAR ENERGY AT THE EARTH'S SURFACE

Solar energy reaching the surface of the earth beneath a heterogeneous cloudy atmosphere is a function of many variables. The irradiance at the surface, Q_s (energy per area per time) is the integral over 2π steradians of the radiance reaching the surface, N_s (energy per area per time per solid angle).

$$N_s(\Theta,\phi) = \frac{Q_o \cos\Theta_o \, e^{-\tau \sec\Theta}}{\Omega} + \frac{Q_o \cos\Theta_o \, f(\Theta,\rho_s)}{\Omega} \qquad (1)$$

Energy reaching the surface may be either direct beam (first term) or diffuse "skylight" radiation (second term). Symbols in equation (1)

are defined as:

ρ_s = surface albedo

Q_o = solar irradiance at "top of the atmosphere" (the solar constant) corrected for earth-sun distance

Θ,ϕ = zenith and azimuth angles, respectively

τ = optical depth of the atmosphere

Ω = solid angle subtended by the sun at the earth

$f(\Theta,\rho_s)$ = function representing diffuse radiation as discussed by Diermendjian and Sekera (1954)

A method for determining Q_s, the total (direct-plus diffuse) radiation and a method for approximating the first term, the direct, follow.

DIRECT PLUS DIFFUSE DETERMINATION

The total broadband visible irradiance received at the top of the earth's atmosphere, Q_o, is balanced by absorption and reflection within an earth-atmosphere column as in equation (2):

$$Q_o = RR_T + RA_A + RA_S \tag{2}$$

where symbols are defined as:

RR_T = total reflected energy to space

RA_A = total absorbed energy within the atmosphere

RA_S = total absorbed energy at the earth's surface

These and other interactions of a single stream of radiation entering the atmosphere from space are shown in Figure 1. No secondary reflections are shown for simplification.

An incoming radiation stream undergoes losses within the atmosphere, other than absorption, due to reflections to space by clouds, RR_C, by variable atmosphere particulates, RR_P, and by background

levels of atmospheric constituents, such as by Rayleigh scattering, RR_B. These three reflections make up the total atmospheric part of reflection to space, RR_A.

The downward directed stream at the earth's surface surviving atmospheric attenuations, Q_S, is balanced by the sum of energy absorbed at the earth's surface, RA_S, and that reflected from the earth's surface, RR_S. This relationship can be shown to be:

$$RA_S = Q_S(1-\rho_s) \tag{3}$$

where ρ_s is the earth's surface albedo, $(\rho_s = RR_S/Q_S)$. All terms shown in Figure 1 can be expressed as fractions of the incoming beam Q_O, and from now on will be shown as lower case letters, i.e., $rr_T = RR_T/Q_O$, etc.

Equation (2) is rewritten using equation (3) and rearranged to give:

$$q_s = \frac{1.0 - rr_T - ra_A}{(1 - \rho_s)} \tag{4}$$

Equation (4) is the relationship for fractional surface solar energy, q_s, to which the satellite data will be applied.

The term rr_T is the actual planetary albedo at the top of the atmosphere measured by the satellite. The term ρ_s, the surface albedo, cannot be measured directly from the satellite but can be estimated by using clear sky albedoes for the earth-atmosphere column. The clear sky albedo can be determined for each area, a grid area, by taking the minimum value measured at that area over some prescribed time period and number of samples. Implicit in the minimum albedo technique is that cloud effects (rr_c) and some variable atmosphere

particulate effects (rr_p) are high frequency phenomena at a given grid area so that at least one sample over the prescribed time period is free of these effects. The clear sky albedo, $(rr_T)_{min}$, is related to the surface albedo, ρ_s, by:

$$(rr_T)_{min} = q_s \, \rho_s \, \tau\uparrow + rr_A\uparrow \tag{5}$$

where $\tau\uparrow$ is the transmittance of the atmosphere to a stream of energy reflected from the earth's surface and $rr_A\uparrow$ is the reflection to space by the atmosphere alone.

Equation (5) can be solved for ρ_s:

$$\rho_s = \frac{(rr_T)_{min} - rr_A\uparrow}{q_s \, \tau\uparrow} \tag{6}$$

The q_s appearing in equation (6) is not the same as the q_s in the equation (4). All terms in equation (6) are for clear sky (cloud free) conditions. The terms q_s, $rr_A\uparrow$ and $\tau\uparrow$ can be estimated well from the nearest surface pyranometer station data with appropriate adjustment for any slight differences in solar zenith angle, ζ. Basically, then, the earth's surface albedo is determined from the clear sky albedo by "tuning" equation (6) with station data.

The remaining term in equation (4) which must be satisfied is ra_A, the cloudy atmosphere fractional absorption. Fortunately, ra_A is the smallest term in the expression (less than 0.25) since it cannot be solved for directly over the satellite measuring domain. It can be estimated sufficiently well by developing empirical relationships based on cloudiness and optical path length due to atmospheric water vapor. This method is similar to Hanson, et al. (1967) and was later refined by Hanson (1971) by explicitly considering cloudiness.

He developed an empirical relationship for the month of June using conventional data so that:

$$ra_A = 0.117 + .031\tau^{\frac{1}{2}} \ln\tau \qquad (7)$$

where τ is computed as a function of cloudiness and optical path length of water vapor. The standard deviation of the residuals from least square fit in equation (7) was 3.2 percent.

<u>Small Scale Reduction</u>. In addition to computing q_s at the spatial scale of the satellite radiance data using equation (4), q_s can be approximated at even smaller scales or at subgrid scales if cloud amount is known at the smaller scale. Consider q_s at the larger scale so that:

$$q_s = a_c\, q_c + a_n\, q_n \qquad (8)$$

where a_c and a_n are the fractional cloud and cloud-free areas over the larger scale, and q_c and q_n are the surface solar energy in the cloudy and cloud-free areas, respectively. Equation (8) can be solved for q_c provided the cloud amount is known. Essentially, q_c and q_n are average values of surface solar energy beneath an average cloud and in the clear regions, respectively. A measure of the distribution of cloudiness over the small scale permits an estimate to be made of the distribution of surface solar energy over the area at a smaller space scale (subgrid scale).

<u>Cloud Area</u>. Cloud cover as seen from satellites can be computed from satellite cloud imagery. Figure 2 is a photograph of cloud images from the Defense Meteorological Satellite Program (DMSP) satellite. The cloud areas can be retrieved from this imagery by either digitizing the photograph or using an optical planimeter. These cloud areas should

be more properly termed as relative cloud amounts since the retrieval of true cloud amount is limited by the resolution of the satellite viewing instrument.

The rectangularly enclosed region in the photograph in the left of Figure 2 has been digitized and is displayed to the right. The total digital signal has been grouped into five classes represented by just five different characters for display purpose. From the digital product relative cloud areas can be computed by selecting an appropriate digital cutoff value for cloudiness.

This approach in getting subgrid scale solar energy at the earth's surface assumes that clouds over the entire large scale area have the same radiative properties. Quite often this will not be the case. However, this approach allows a best estimate of total surface solar energy at the smaller scale in lieu of direct ground measurements.

Direct Beam Approximation. The direct beam solar energy is estimated with an assumption that clouds, other than thin transparent clouds, have a binary effect on it. That is, in the presence of a cloud, only diffuse solar energy reaches the earth's surface beneath a cloud. With this assumption direct reflections from adjacent clouds are not considered. Thus, direct beam solar energy is received at the earth's surface only in the cloud free area.

This method is to be applied over a small region, such as a city, using very high resolution satellite cloud imagery. For it to work well, individual clouds should be distinguishable in the imagery. A prior knowledge from surface measurements using pyranometer and pyrheliometer instruments is required to separate the diffuse and direct solar energy in the clear areas.

If equation (8) is applied to the very high resolution data in regions where larger scale q_s has been computed, then diffuse radiation at the surface in cloud areas can be estimated at the smaller scale too. Therefore, both direct and diffuse energies received at the earth's surface can be evaluated and statistics can be compiled on them.

In the total and direct beam methods just described, the primary role of the satellite observation is to consider the effect of horizontal inhomogeneities in cloudiness over an area rather than just scattered point values of insolation. Since clouds are the principle modulators of surface insolation, a solar energy climatology generated by these methods should be more representative than that generated by previous methods which were not augmented with satellite data.

ACKNOWLEDGMENTS

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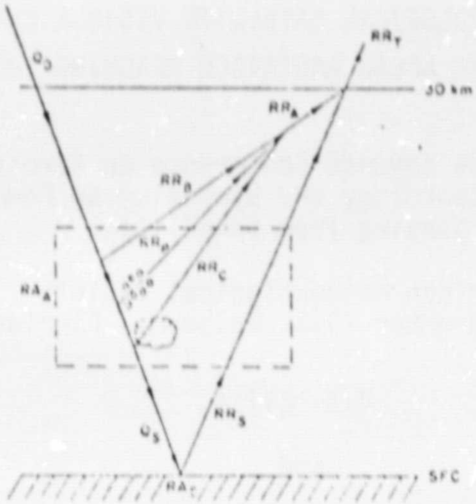

Figure 1. A stream of solar radiation in the earth-atmosphere column.

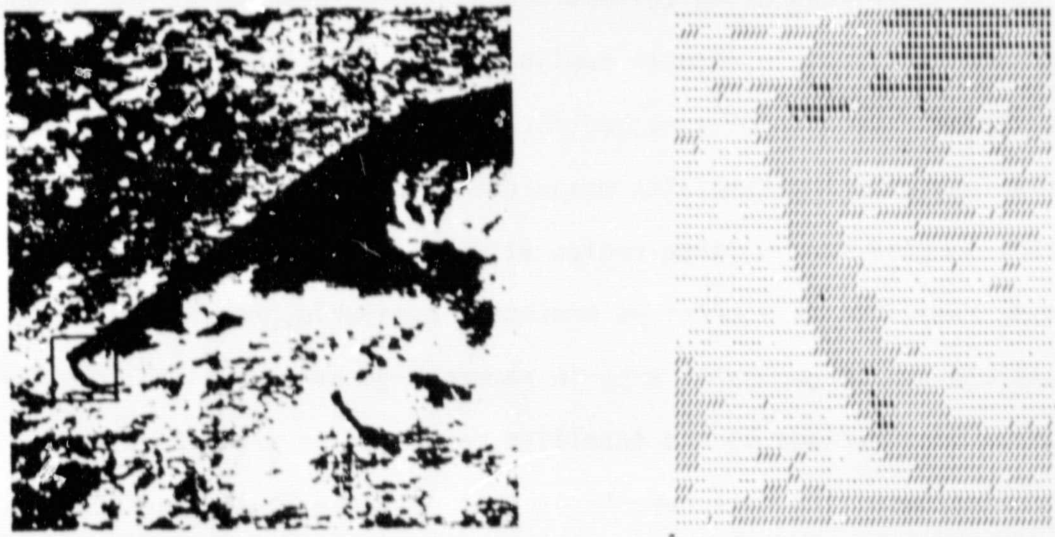

Figure 2. Photograph of the western Lake Superior region from DMSP satellite and a digital representation of the rectangularly outlined area.

APPLICATION OF METEOROLOGICAL SATELLITE VISIBLE CHANNEL RADIANCES FOR DETERMINING SOLAR RADIATION REACHING THE GROUND

Presented at the Seventh Conference on Aerospace and Aeronautical Meteorology and Symposium on Remote Sensing from Satellites

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Appendix A-2

INTRODUCTION

The purposes of this paper is to demonstrate a method for determining mean daily solar insolation (direct and diffuse) received at the ground using satellite visible channel radiance measurements. The method is basically an expansion of a method first demonstrated by Hanson (1971). An advantage of using satellite measurements is that one instrument can take samples over a large region at fairly high spatial resolution. By using satellite data archives presently available, an insolation climatology can be generated even in remote regions at minimal cost. A principal disadvantage to the satellite method using archived sun-synchronous satellite measurements is that just one measurement for each day at each ground position is taken. Thus, regions with significant diurnal cloudiness variations are not adequately sampled. However, using geosynchronous satellite measurements, such as those from a well calibrated SMS/GOES satellite, would eliminate the diurnal sampling problem.

A window, enclosing the contiguous United States, was extracted from the global archive of NOAA sun-synchronous satellite measurements for 30 days of June 1975 to demonstrate the method. The data are geometrically normalized into albedos and combined with ground elevation, precipitable water, and global pyranometer data to arrive at a high spatial resolution, mean daily insolation for the month.

SATELLITE METHOD

Total (direct-plus-diffuse) incoming solar flux at the ground can be expressed in an energy balance equation of an earth-atmosphere column. The development of this expression is taken from Hanson, et al. (1976). It is normalized by dividing through by Q_o to get:

$$1 = q_r + q_a + q_g \tag{1}$$

and

$$q_g = (1.0 - \rho_s)\, q_s \tag{2}$$

where:

q_x = Q_x/Q_o

Q_o = incident solar flux at top of atmosphere

q_r = fractionally reflected shortwave flux

q_a = fractional absorbed shortwave flux within the atmosphere

q_g = fractional absorbed shortwave flux at the ground

q_s = fractional incident solar flux at the ground

ρ_s = ground surface albedo

From (1) and (2) one can obtain q_s such that:

$$q_s = \frac{1.0 - q_r - q_a}{(1.0 - \rho_s)} \tag{3}$$

Satellite visible channel radiance measurements are applied to (3) to obtain q_s. Now q_r is the actual planetary albedo which can be determined directly from satellite measurements with appropriate angular corrections. These corrections are discussed in the next section. The absorbed shortwave flux, q_a, can be determined as a residual in (3) at sites where incident global solar flux is measured. Hanson (1971) discussed the development of an empirical formula at these sites which is then applied away from the sites. In effect, it allows one to extrapolate away from the sites using a statistical-empirical formula. His method is to compute values of total optical pathlength, τ, and with determined q_a values, find coefficients to a functional relationship between the two using least squares.

$$q_a = C_1 + C_2 \, \tau^{\frac{1}{2}} \ln \tau \tag{4}$$

and considering diffuse radiation beneath clouds:

$$\tau = (1\text{-Ac})\ (.86\ u^{*}+.14(1.66\ u)) + A_c(1.66\ u) \tag{5}$$

where:

A_c = fractional cloud amount

u = optical depth of water vapor for clear sky (precipitable water)

u^{*} = $u/\cos\bar{\zeta}, \bar{\zeta}$ is average, cosine weighted, daytime solar zenith angle.

This basic method was expanded in the present application. The fractional cloud amount, A_c, is approximated from the satellite determined albedo rather than using scattered ground observations of A_c. An obvious advantage to measuring A_c from a satellite platform is the consistent and very good spatial sampling capability of the satellite, even in remote regions of the earth. A method similar to that of Reynolds and Vonder Haar (1976) is used to approximate A_c.

$$A_c = \frac{q_r - q_{clr}}{q_{cld} - q_{clr}} \tag{6}$$

where:

q_{clr} = cloud free planetary albedo

q_{cld} = planetary albedo over clouds (set at 0.50)

They showed quite favorable results from many test cases for three different sites.

The study was further expanded by approximating ground albedo ρ_s, with a cloud free albedo at the top of the atmosphere. In most cases the two differ because of atmospheric absorption and scattering. However, the difference is virtually never more than 5 percent in real atmospheres (Cox, 1975). This difference does not severely affect the results in the study as is shown by an uncertainty analysis in a later section. Furthermore, cloud free albedos, which are determined by retaining a minimum value of albedo at each grid spot on earth over some time period, are most likely more accurate than values extrapolated from rather sparse surface albedo measurements.

DATA REQUIREMENTS

Data needed to apply this method included calibrated visible-channel satellite radiance measurements, 12 hourly rawinsondes, and a number of well calibrated, global solar flux measurements at the ground.

The method was tested on the month of June 1975 using NOAA 4 scanning radiometer (SR) visible channel photometric measurements. The SR data from NOAA satellites are archived by the National Climatic Center as normalized brightness values. The archive extends back to 1973 to include NOAA 2, 3, and 4 measurements. The measured brightness

values were normalized before archival by dividing each by cos ζ (ζ is the solar zenith angle at time of measurement). Ground resolution of the archived data are about 10 km over the contiguous United States.

The region where the method was applied is shown in a window extracted for 11 June 1975 from the NOAA 4 global data set of normalized brightness (Fig. 1). Picture quality is reduced considerably because 4 x 4 grid elements were taken together to obtain levels of gray shading on a microfilm plotter.

The archived data must be converted to radiometric units from photometric units, and corrected for angular dependence of reflecting surfaces in the field of view. A model for correcting for angular dependence has been discussed in detail by Raschke, et al. (1973). It corrects for bidirectional reflectance characteristics of a grid element giving an integrated global flux over 2π steradians. These instantaneous flux values are further normalized to mean daytime flux values by applying a reflectance model which allows for changing albedo with changing solar zenith angle.

Angular corrections to be applied to the archived normalized brightness values in order to obtain mean daytime flux are shown in Fig. 2 for just one day, 1 June 1975. Three separate orbital swaths were mapped in this particular window. A discontinuity in correction factors is seen at the overlap boundaries along with an increase in values from left to right for each swath.

Optical pathlengths due to water vapor, u, are computed from 12 hourly rawinsonde observations within the window. The u values are objectively analyzed daily and interpolated to grid points, corresponding to the NMC prediction grid using a Cressman (1959) type scheme. The values at the NMC grid spacing are linearly interpolated to the NMC superset

grid spacing of the to the NOAA 4 archive. They are further adjusted for variations in ground elevation allowing for a linear decrease of u in the vertical with an increase in ground elevation. Ground elevations, mapped to the nearest 10 meters on the NMC superset grid, are displayed in Fig. 3 for the window.

Finally, incident global solar flux at the earth's surface is taken from the NWS surface pyranometer network of measurements. From this network, sites which have well calibrated Epply Model II pyranometers were selected. Just the 9 sites shown in Fig. 4 satisfied this criteron in June 1975. Remaining sites of the network were not included because of large uncertainty in their absolute calibration and relative measurement accuracy (see Hanson, 1973 for discussion of uncertainties in the network measurements).

UNCERTAINTY IN THE RESULTS

The method not only allows for high spatial global solar flux determination at the ground but also gives results at the ground comparable in quality to *in situ* measurements. A complete uncertainty analysis of both independent and dependent measurement error shows an uncertainty in the results of less than 6 percent of the incident solar flux at the top of the atmosphere, or less than 8 percent of the clear sky value. However, these results assume no diurnal change in cloudiness and other atmospheric constituents. Of course, this assumption is not valid at many locations during various seasons of the year. Considering diurnal changes, an uncertainty closer to 10 percent in daily mean values seems reasonable. Since computations are made daily, statistics of various types other than just mean daily values can be generated. These statistics include variances and consecutive days of solar insolation

below some critical value. Furthermore, a number of additional products can be generated from the elements of the study. These include a representation of cloudiness statistics and atmospheric absorption statistics.

Finally, results of the study will be presented at the conference.

ACKNOWLEDGMENTS

The authors thank Messrs. David Wackter and Wayne Bowers for assisting in the tremendous amount of data processing. This work was performed under NASA Grant NAS5-22372. Computer resources were provided at the National Center for Atmospheric Research which is sponsored by the National Science Foundation.

Figure 1. NOAA 4 normalized brightness for 11 June 1975.

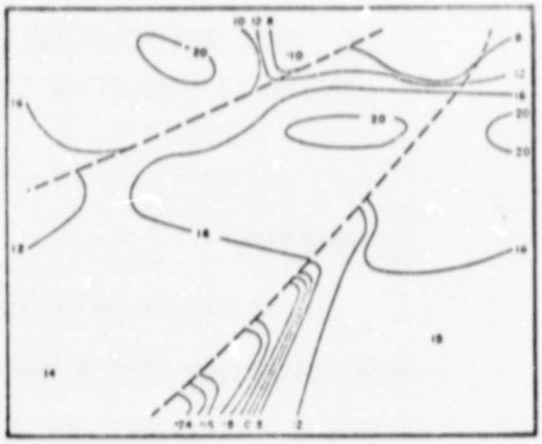

Fig. 2. Angular corrections in percent to normalized NOAA satellite archive, 1 June 1975.

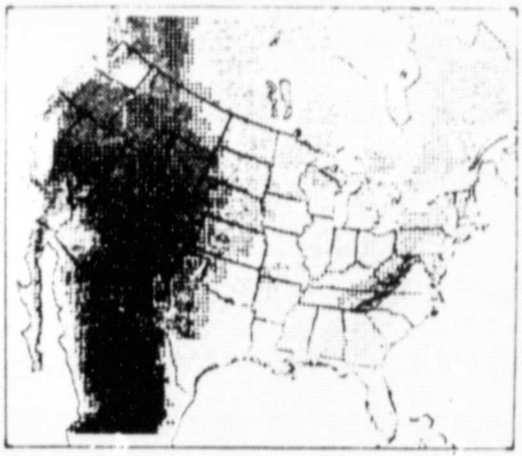

Fig. 3. Ground elevation mapped to NMC superset grid.

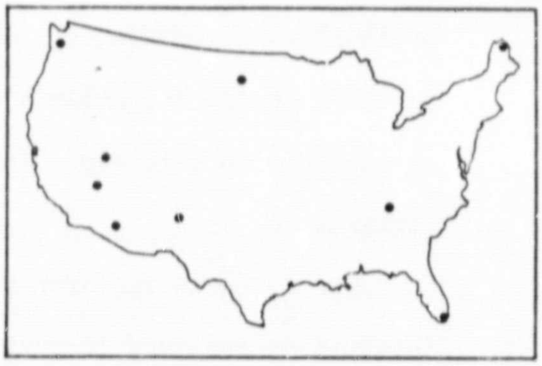

Fig. 4. Eppley Model II pyranometer sites in NWS network, June 1975.

DATA ASSIMILATION AND COMPUTATION NETWORK OF EVENTS LEADING TO INSOLATION COMPUTATION FROM SATELLITE MEASUREMENTS

Appendix B

INTRODUCTION

The solar energy microclimate study involves quite a few different data sets along with a number of operations to be performed on each data set. It seems best to discuss the program by referring to a simple network of identifiable events which take place for program completion.

Three generalized networks are discussed in the following order: calibration and calibration verification network, data processing and mean insolation network, and statistics generation network. Events of the networks are coded for reference to documentation.

CALIBRATION NETWORK

The NOAA satellite scanning radiometers are calibrated photometrically in luminance. The digital mapped data archive, mapped to a northern hemisphere polar steriographic daily mosaic, is in the form of counts from 0 to 255. These counts are related linearly to foot-lamberts.

Our research requires radiance data (Wm^{-2} sr^{-1}). All calibration information required to make the transformation from luminance to radiance has been received except for spectral radiance profiles of each calibration lamp.* These profiles, representative of the lamp type used in the calibration, are most likely available. A representative from NOAA/NESS

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* A spectral radiance profile for the calibration lamp-system was received from A. Schwalb, NOAA (ref. Jones et al., 1965).

Jones, G.D., D.T. Hilleary, and B. Fridovich, 1965: A diffuse light source for calibrating meteorological satellite television cameras. Applied Optics, 4, 3.

is trying to obtain this profile information for us from Santa Barbara Research Center.

The original plan for both calibration and calibration verification is shown by the calibration network in Figure 1. Each event is discussed separately in numbered sequence as follows:

1. Obtain calibration lar information.
2. Obtain NOAA satellite scanning radiometer calibration test data sets. Four sets were obtained to compare with ATS-6 GVHRR visible channel data and one set to compare with Nimbus 6 ERB scanner data.
3. Develop program to retrieve angles specifying geometry between satellite, sun and target.
4. Apply calibration, angle retrieval program, and bi-directional reflectance model to NOAA-SR test set to obtain reflected flux and albedo.
5. Obtain ATS-6 GVHRR data set to check NOAA-SR calibration. The ATS-6 data were not delivered from NASA/GSFC due to data reduction problems. We proceeded without this calibration check.
6. Apply bi-directional reflectance model to ATS-6 data (did not do).
7. Compare NOAA-SR and ATS-6 simultaneous flux data for the selected target as a calibration check. One of the targets is White Sands Missile Range (did not do).
8. Obtain Nimbus-6 ERB scanner data set to check NOAA-SR calibration.
9. Compare NOAA-SR and Nimbus 6 flux data for selected targets as a calibration check on the NOAA-SR data.

MEAN SOLAR INSOLATION NETWORK

This network explains the sequence of events for computing mean monthly solar insolation at the ground.

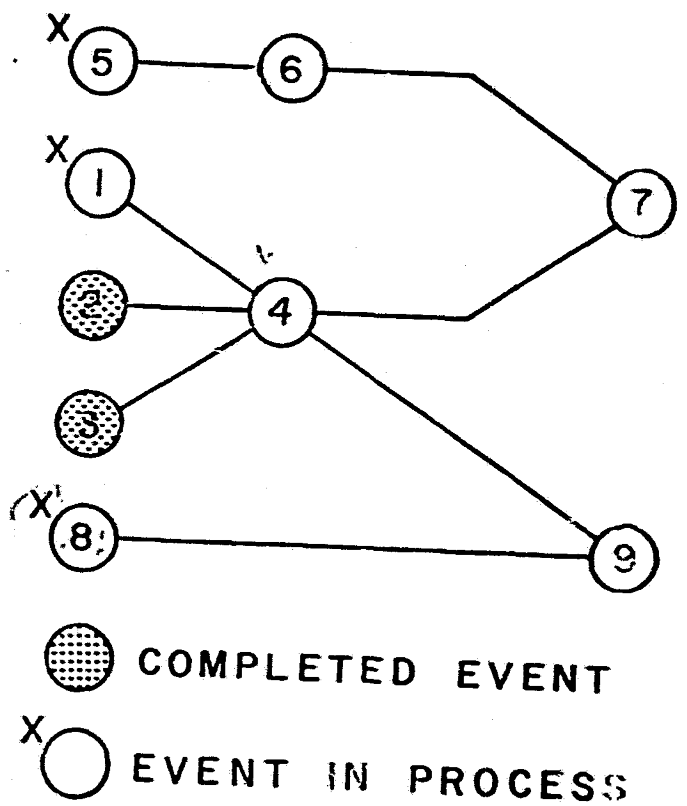

Figure 1: Calibration and Calibration Verification Network

The sequence of events and the status of each event is displayed in the mean insolation network of Figure 2. Each event is discussed as follows:

1. Complete calibration, compute satellite-sun-target geometry, apply bi-directional reflectance model and evaluate reflected flux by comparison with other calibrated satellite flux data. This event is explained in detail in the previous section on calibration.
2. Obtain NOAA-SR data.
3. Apply results from event 1 to the satellite data to obtain daily reflected flux to space.
4. Compute minimum albedo which is a nearly cloud-free albedo.
5. Compute monthly average albedo.
6. Complete development of a cloudiness parameter (effective could amount) which is to be derived from daily albedo and minimum albedo.
7. Obtain global solar pyranometer data for selected sites in the continental United States. Data from 9 sites with newer model Eppley pyranometers were received.
8. Compute shortwave flux absorption in the atmosphere over the 9 pyranometer sites and normalize this absorption to a fractional absorption.
9. Obtain daily RAOB data for all United States' stations.
10. Compute daily optical path length due to water vapor for each RAOB station.

11. Parameterize atmospheric absorption over the nine surface pyranometer sites using satellite derived cloud parameter and optical path length results.
12. Begin research on how the atmosphere absorption parameterization is to be partitioned in space. The parameterization will differ for each of the 9 sites. Some alternatives are to group parameterizations by geography, by air mass type, or combine all of them together into one parameterization. The last alternative may prove to be best with implementation of our new cloudiness parameter.
13. Complete research on atmospheric absorption parameterization.
14. Obtain a complete set of station RAOB data for the entire continental United States. (Same as 9 above).
15. Compile monthly mean "normal" optical path length due to water vapor for each station.
16. Obtain terrain height data for every five minutes of latitude and longitude.
17. Interpolate terrain height field to same grid as NOAA-SR satellite data.
18. Interpolate "normal" optical path length in three dimensions to NOAA-SR grid using interpolated terrain height field; and apply mean solar zenith factor to obtain gridded optical path length due to water vapor.
19. Apply atmospheric absorption parameterization to the gridded optical path length field and the cloudiness parameter to obtain atmospheric absorption at each NOAA-SR grid point.

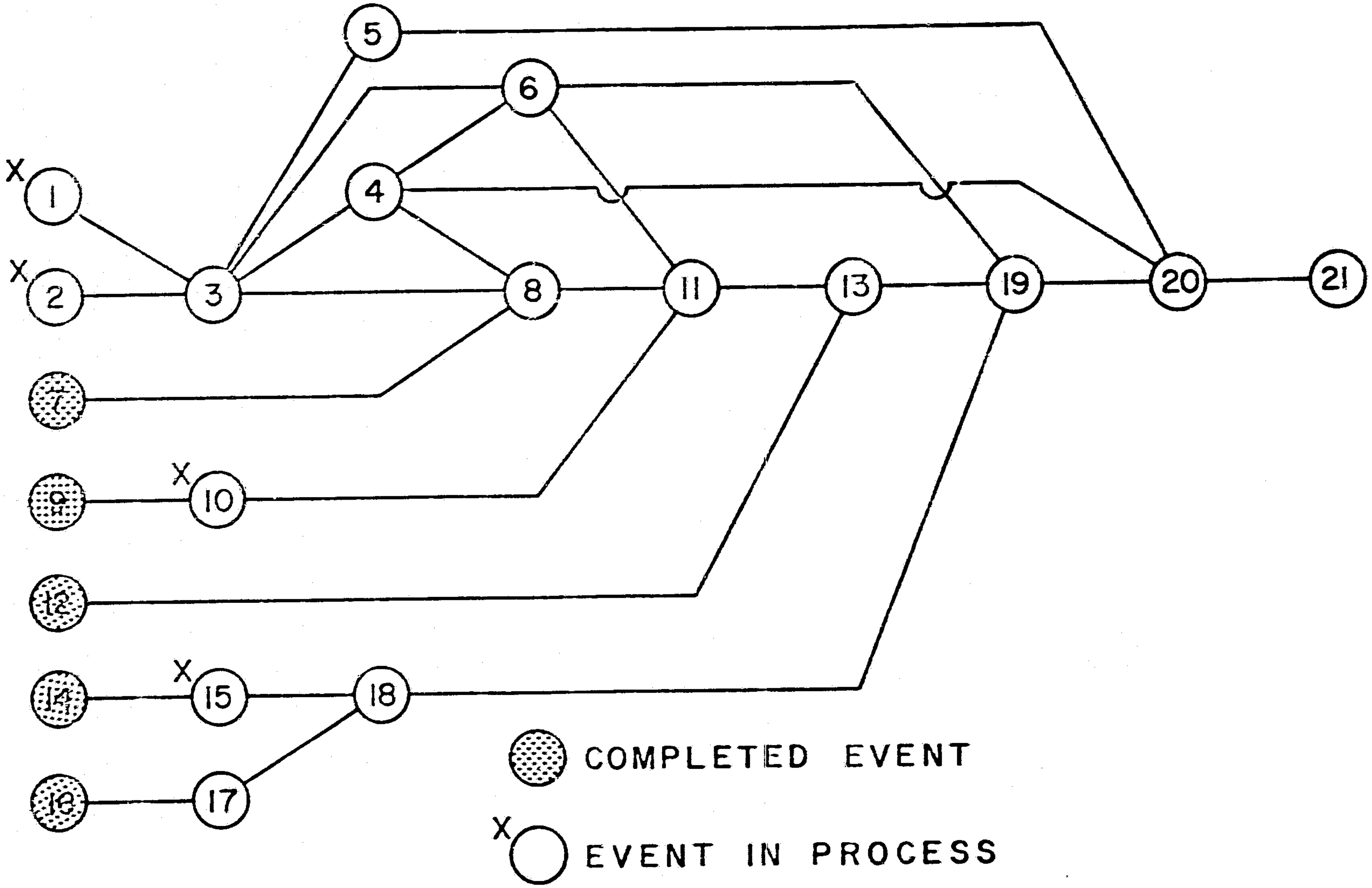

Figure 2: Data Processing and Mean Insolation Network

20. Combine monthly mean albedo, minimum albedo, and atmospheric absorption to obtain mean monthly fractional surface solar insolation in the NOAA-SR grid.

21. Convert fractional insolation to solar insolation received at the earth's surface. This merely involves multiplying fractional insolation by solar insolation received at the top of the atmosphere.

STATISTICS NETWORK

Statistics besides the mean can be calculated which include consecutive days below some threshold value, the range, standard deviation, and etc. These calculations cannot begin, of course, until the data processing is under way as depicted in the mean network of Figure 2.

The flow of these events can occur simultaneously with the processing in Figure 2 by applying daily values of albedo and optical path length of each grid point in events 20 and 19 respectively. All beginning events in Figure 3 pertain to Figure 2 and are discussed in the previous section. All other events of Figure 3 are as follows:

21. Compute monthly mean surface insolation at each grid point. This event, as discussed in the previous section, may be modified to follow after event 24 in Figure 3.

22. Compute daily absorbed solar energy in the atmosphere by applying absorption parameterizations.

23. Compute daily fractional insolation at the earth's surface at each grid point.

24. Change gridded fractional insolation to gridded insolation.

25. Compute consecutive days of below threshold statistics.

26. Compute variance statistics.

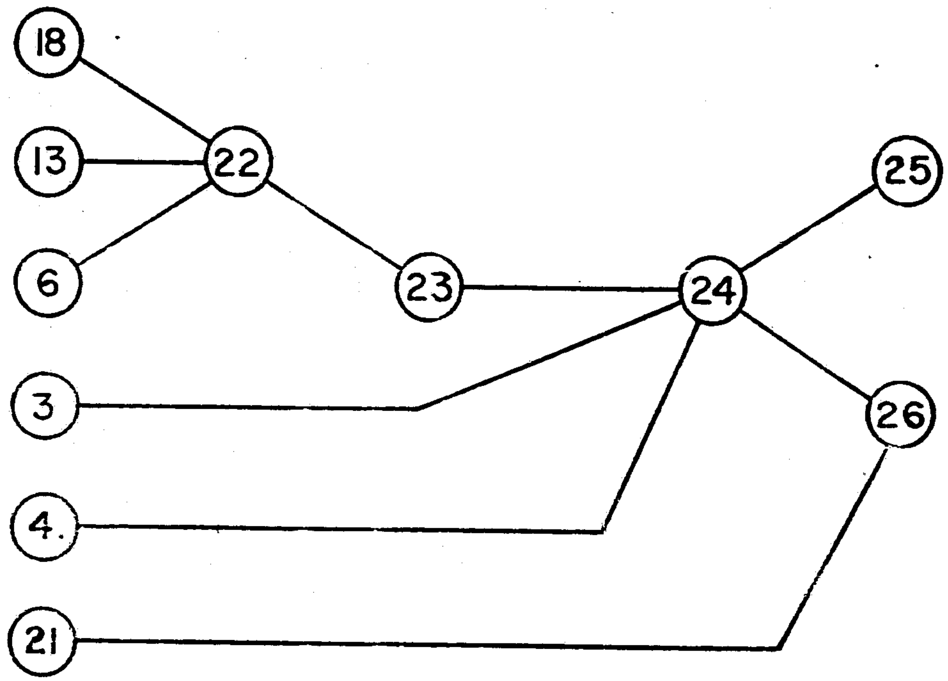

Figure 3: Statistics Network

ALL DIGITAL VIDEO IMAGING SYSTEM FOR ATMOSPHERIC RESEARCH (ADVISAR)

Appendix C

The Advisar system is an all purpose image processing system oriented toward research and development in the atmospheric and earth sciences with particular emphasis on satellite imagery. The overall system is described in terms of its five component subsystems:

1. Computer Hardware and Peripherals
2. Video Display Hardware and Control
3. Digitizing Hardware and Control
4. System Executive Software
5. Applications Software

1. Computer Subsystem

The control system consists of a Hewlett Packard 2100-A computer configured with 32K memory (16 bit words), 16 I/O ports, and 2 DMA channels. This mini-computer is responsible for both video display and digitizing control along with applications software execution (data analysis). The peripheral hardware available to the computer presently consists of:

1. One 20 megabit digital disk unit for both executive/application software and imagery data storage.
2. One 45 IPS 7-track tape drive (200 BPI, 556 BPI, 800 BPI).
3. One 45 IPS 9-track tape drive (800 BPI, 1600 BPI).
4. One 200 cpm card reader.
5. One 2400 baud CRT and keyboard operator terminal.
6. One hard copy and keyboard terminal.

The HP 2100-A is utilized as a multi-terminal system under the control of an HP executive monitor. Software development and video display operations may occur simultaneously with very little cross terminal interference. All software is cataloged to the disk unit such that user operation consists of activating dial-up program commands. Programs are developed at either of the keyboard consoles or at the card reader depending on program length and complexity. Much effort goes into modularizing software as FORTRAN subroutines such that redundancy is minimized and compatibility with other systems is increased. The two tape drives are available for both digital imagery imput and output.

2. Video Display Subsystem

The video display subsystem presently consists of a 512 x 512 spot Hughes scan converter (video refresh memory), a CONRAC color monitor and a hand operated joystick linked to a single spot flashing cursor. This system was integrated and interfaced to the HP computer by Spatial Data Inc. The HP 2100-A is responsible for all data transfer to and from the scan converter; both imagery data and graphic displays can be output to the scan converter memory. Analog controls allow an image to be color enhanced during the display period; black and white enhancement is available under computer control. Another control provides a gradient field display at the flip of a switch. An analog planimeter is also available. The joystick is used to communicate coordinate requests as applied to the displayed image while a cursor tracks the joystick motion. There is an option to permanently depict a cursor location.

3. Digitizing Subsystem

The digitizing capability is provided by a Spatial Data 108 control system coupled to a Telemation (model TMC-2100) vidicon camera. Any portion of a photo transparency (positive or negative) can be digitized to a resolution of 8-bits (256 levels) under computer control and output to tape, disk, or scan converter. An auxillary B/W monitor is utilized to portray the photographic sector undergoing digitization.

4. System Software

The operating environment is under the control of the HP Real Time Executive Monitor (RTE). This system has been minimally modified to provide an image processing mode convenient to R & D level users. All applications software is cataloged by the disk file monitor such that it is easily modified or edited for special applications.

5. Applications Software

Basic applications software is available on the computer disk to provide:

1. Digitizing control.
2. Image sector tape and disk I/O.
3. Image enhancement.
4. Graphics display.
5. Analog to digital conversion

Much of the software is being redeveloped for a new, video display system. The future system will consist of eight 512 x 512 solid state video refresh memories configured with dynamic enhancement tables and frame sequencing capability. Individual frame resolution will be 8-bits

or 256 levels. A computer driven cursor will replace the present analog cursor such that coordinate communication will contain zero error. Since this video refresh memory will serve as an auxillary bulk image storage device to the computer, much of the present disk space allocated for image storage will be released for new, permanent applications software. Most of the new software will consist of meteorological parameter extraction techniques as applied to satellite data.

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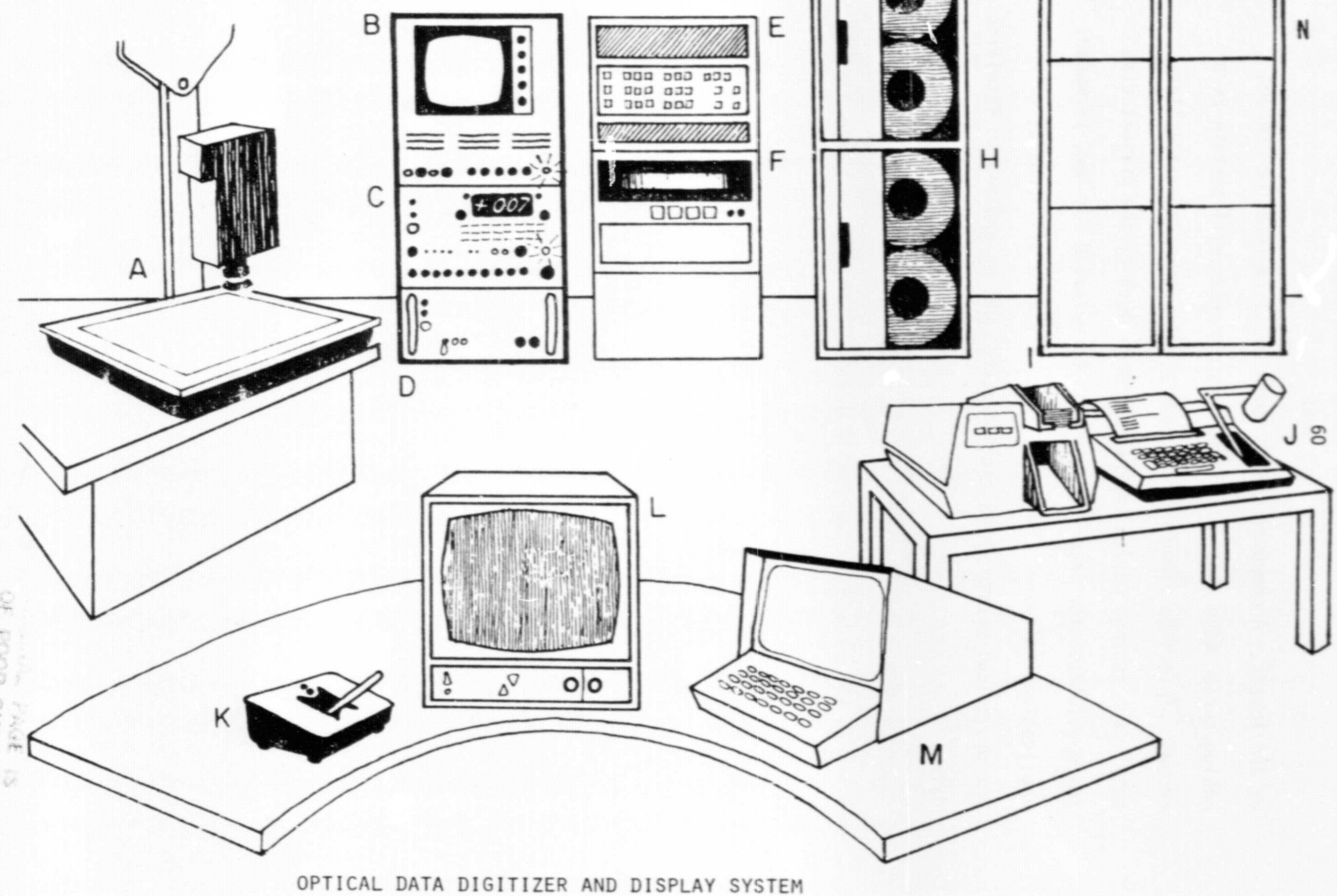

OPTICAL DATA DIGITIZER AND DISPLAY SYSTEM
DEPARTMENT OF ATMOSPHERIC SCIENCE, COLORADO STATE UNIVERSITY

OD^3 HARDWARE COMPONENTS

A DIGITIZING SUB-SYSTEM

B 108 CONTROLLER AND B/W MONITOR

C DATA COLOR EDGE ENHANCER

D SCAN CONVERTER

E HP 2100-A COMPUTER

F DIGITAL DISK

G 9 TRACK DRIVE

H 7 TRACK DRIVE

I CARD READER

J SYSTEM TELEPRINTER AND KEYBOARD

K JOYSTICK

L COLOR DISPLAY MONITOR

M OPERATOR CRT AND KEYBOARD

N SOLID STATE RAPID VIDEO REFRESH MEMORIES

APPENDIX D

Papers Sponsored by NASA Grant No. NAS5-22372

1. Vonder Haar, Thomas H., 1974: Solar insolation microclimate determined using satellite data. Published in the proceedings of the solar Energy Data Workshop, 29-30 November 1973. NSF-RA-N-74-062.

2. Ellis, James S. and T. H. Vonder Haar, 1976: Application of meteorological satellite visible channel radiances for determining solar radiation reaching the ground. Presented at the Seventh Conference of Aerospace and Aeronautical Meteorology and Symposium on Remote Sensing from Satellites, American Meteorological Society, 16-17 November 1976, Melbourne, Florida.

3. Vonder Haar, T. H. and J. S. Ellis, 1975: Solar energy microclimate as determined from satellite observations. Proceedings of the 19th Technical Symposium of Photo-Optical Instrumentation Engineers, 18-22 August 1975, San Diego, CA.

4. Vonder Haar, T. H., 1977: Testimony before the Solar Energy Hearing of the Subcommitte on Energy Production and Supply and the Subcommittee on Energy Research and Development of the Committee on Energy and Natural Resources, and the Select Committee on Small Business, United States Senate, Golden, CO. 1 June 1977. 6 pp.

APPENDIX E

Testimony before the Solar Energy Hearing
of the
Subcommittee on Energy Production and Supply
and the Subcommittee on Energy Research and
Development of the Committee on Energy and
Natural Resources, and the Select Committee on
Small Business, United States Senate

In the chair: Senator Floyd K. Haskell

Metals Hall, Green Center, Colorado School of Mines
Golden, Colorado
Wednesday, June 1, 1977

by Professor Thomas H. Vonder Haar, Head
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Senator Haskell, ladies and gentlemen:

Thank you very much for the invitation to present a statement during these hearings. My testimony is primarily that of an expert witness regarding the transmission of solar energy through the atmosphere and the distribution and amount of solar energy reaching the ground. For several years my colleagues and I have carried out research in these areas using measurements of solar energy, clouds and weather data obtained from weather stations at the ground and from small weather satellites. Our research has been supported by state and federal grants, most recently from NASA and from the Colorado Energy Research Institute.

Homeowners and businesses considering the use of solar energy need to know how much solar energy is normally available at the site of their home or business. Our research results demonstrate that we can provide this information about any location in the United States.

The key component in our new capability is the use of measurements from the new weather satellites.

An example of a map showing the amount of solar energy reaching the ground during our research test period of June, 1975, is included as an attachment to this testimony. This "big picture", a map of average daily solar radiation reaching the ground over the entire U.S., shows that during this month some typical regional values were as follows:

Region	Amount Available Solar energy (calories per square centimeter per day[1])
NW Washington	450
Northern Minnesota	450
New Jersey	475
Houston-Galveston	450
Florida	500
Missouri	550
Northern Utah	600
Rocky Mountain of Colorado and New Mexico	700
Northern Central California	750

Some of these numbers may seem surprising; for example, that northern California received 50% more solar energy than Florida during June, 1975. However, this emphasizes the role of variable weather conditions on the solar energy supply. Using our satellite-based method (together with a few ground stations maintained by the National Weather Service, NOAA), we can determine maps of solar energy reaching the ground for enough months and seasons to give reliable statistics on available solar energy to all

[1] 1 calorie/cm^2 day = 0.15 BTU per square foot per hour.

potential users. Since the weather satellites are planned to continue through the 1980's and beyond, we can expect to update as needed our information about solar energy reaching all areas of the U.S.

The second attachment is a part of a weather satellite photo showing how very detailed views of the solar energy microclimate are possible. It displays the western tip of Lake Superior, including the city of Duluth, Minnesota, at a time when some ice was separated from the southwest shore by a narrow band of open water. Also shown is the computer output map of the same small region; to illustrate how we process the satellite data by computer to obtain the amount of solar energy reaching the ground. The very high resolution satellite views are often important to solar energy users because even the average solar energy supply can change as much as 20% in 20 miles near cities, mountains, coasts, etc.

Our results thus far have demonstrated that we can use new methods to make available information about solar energy supply needed by solar energy users. They are documented in the FINAL REPORT under NASA Grant NAS5-22372 entitled: Determination of Solar Energy Microclimate of the United States Using Satellite Data by Thomas H. Vonder Haar and James S. Ellis, Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523, April, 1977. I will provide copies of this report to Senator Haskell and to staff members of the various subcommittees. Additional copies are available on request from my office. Our report also includes results for October, 1975, and explains the solar radiation transfer methods and computer processing techniques available at Colorado State University.

What is needed to fully benefit from these preliminary research results? How can these results help us reach President Carter's stated goal of using

solar energy in 2.5 million homes by 1985? What should Congress do? In response to these questions posed by Senator Haskell, I conclude my testimony with several recommendations:

1) We should expand the preliminary results with a renewed research effort to assess the detailed capabilities of using weather satellite data to determine the solar energy reaching the ground over the United States. In order to provide definitive information about the solar energy supply during all seasons; about the best processing methods; and to determine the uncertainty level of the results, a good deal of data must be processed. I estimate the need for a two year effort costing $400,000 to $500,000; it could begin immediately. Based on our preliminary results, the probability of success is high and the results of the two-year study ending in late 1979 would be of immediate use to solar energy users. A publication containing solar energy supply statistics and maps could be distributed to homeowners and businessmen through the government printing office, university extension offices, and by solar energy businessmen.

2) Appropriate energy research groups should determine the economic value of <u>updated</u> solar energy supply data and, possibly, solar energy supply forecasting.

3) Based on results from (1) and (2) above, we should consider the establishment of an operational solar energy supply monitoring program, using both satellite and ground-station measurements, under the auspices of the appropriate federal agency.

---- End of testimony by T. H. Vonder Haar
ATTACHMENTS (2 figures)

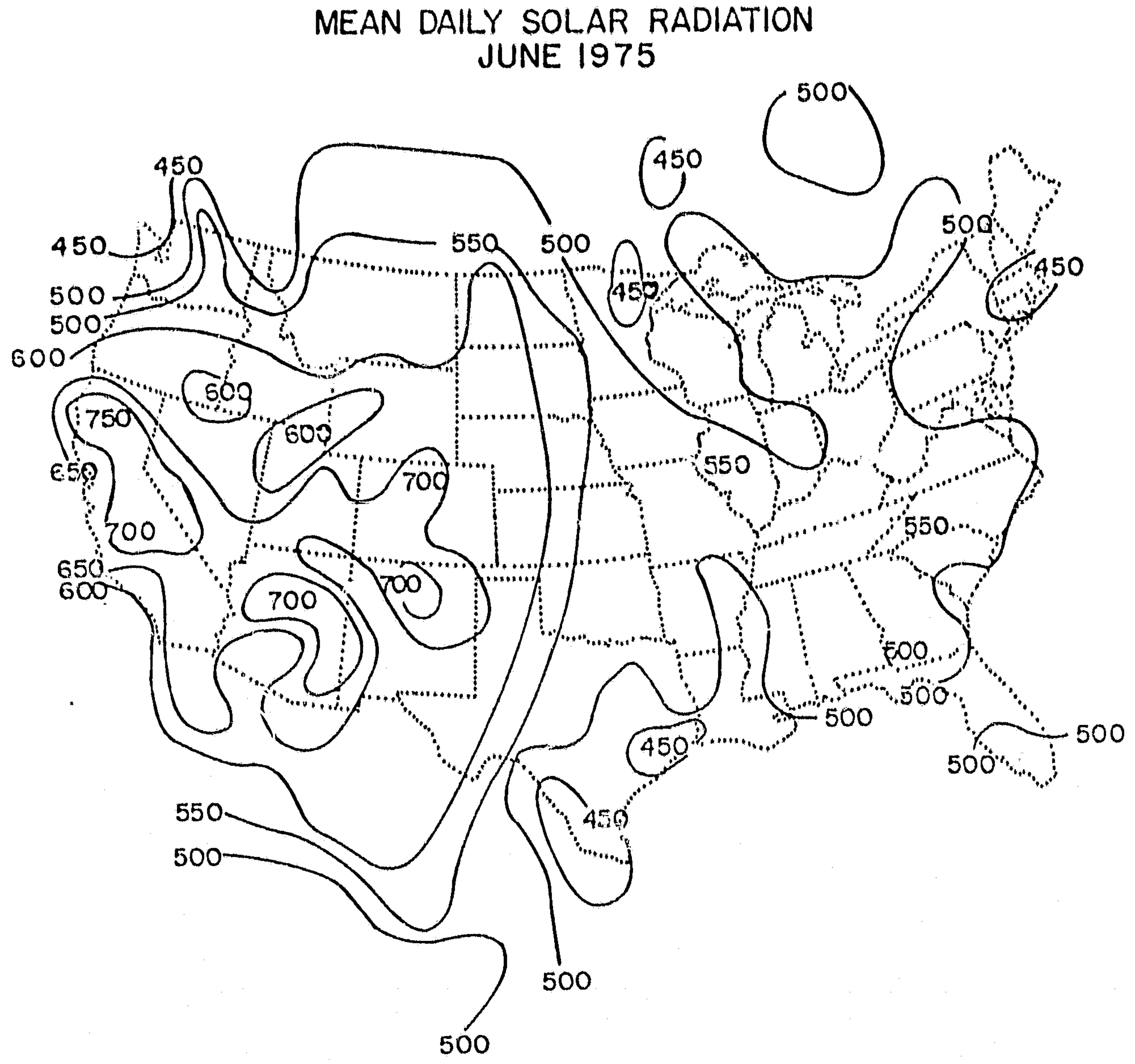

Figure 1. Mean daily solar radiation reaching the ground over the United States during June 1975 as determined from weather satellite observations. Values are in calories per square centimeter per day. (1 calorie/cm^2 day = 0.15 BTU per square foot per hour)

Taken from the Final Report for NASA Grant NAS5-22372, "Determination of Solar Energy Microclimate of the United States Using Satellite Data" by Thomas Vonder Haar and James Ellis of the Department of Atmospheric Science, Colorado State University, Ft. Collins, CO April, 1977.

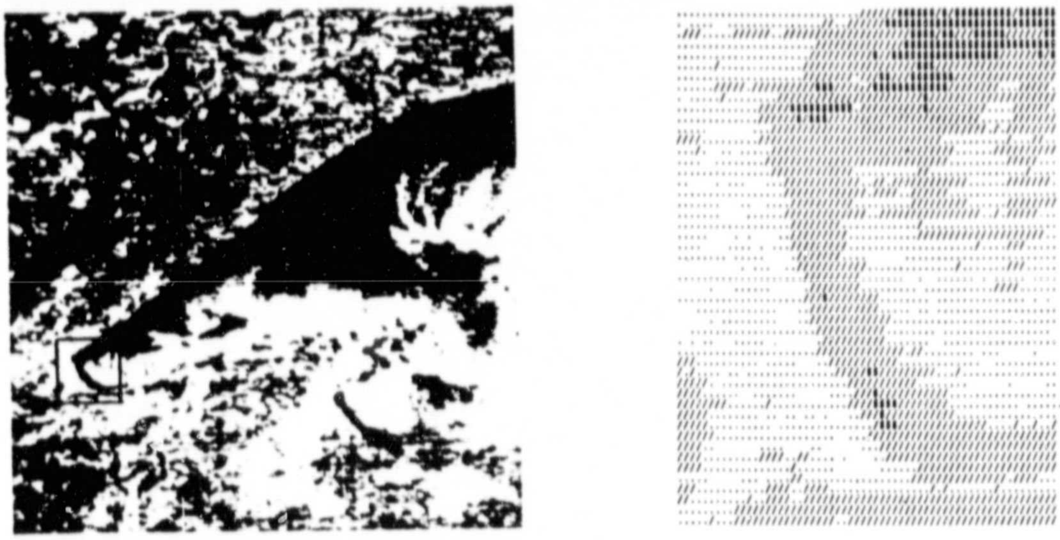

Figure 2. Photograph of the western Lake Superior region from DMSP satellite and a digital representation of the rectangularly outlined area.

Taken from "Solar Energy Microclimate as Determined from Satellite Observations" by T.H. Vonder Haar and J.S. Ellis of the Atmospheric Science Department at Colorado State University, Fort Collins, CO; presented at the meeting on Optics in Solar Energy Utilization, August 21-22, 1975, San Diego, California.